Fundamentals of Electric Drives

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Lecture 33

Open-loop V/f control, Torque-speed characteristics, Self controlled synchronous motor drive employing load commutated thyristor inverter

Hello and welcome to this lecture on the fundamentals of electric drives. In our previous session, we delved into the topic of synchronous motor drives, where we explored their operation and characteristics. We learned that synchronous motor drives can be broadly classified into two categories: the true synchronous mode and the self-controlled mode. These are the two distinct types of synchronous motor drive systems that we covered in detail during our last lecture.

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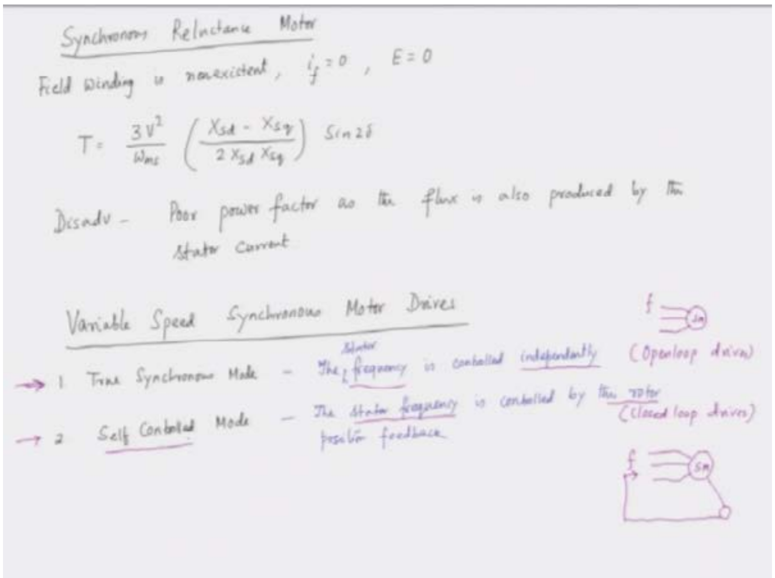

In this case, the stator frequency is independently controlled, much like a conventional synchronous machine fed from a supply with possibly variable voltage and frequency. However, there are other types of synchronous motor drives where closed-loop feedback is essential to regulate the stator frequency, this type is known as the self-controlled drive.

In the self-controlled mode, the stator frequency is governed by the rotor. This synchronization between the stator and rotor is crucial because, in a synchronous machine, the rotor must always remain in sync with the stator field.

Now, when the machine is powered by an independent source, such as in the true synchronous mode, the frequency f is determined by that source. This setup, however, can lead to instability. The machine might experience hunting or oscillations because the stator frequency is not directly linked to the rotor speed. As a result, the rotor may attempt to adjust itself to the stator frequency, causing instability.

On the other hand, in a self-controlled drive, the rotor itself determines the stator frequency. A position sensor, or rotor position sensor, is used to track the rotor's speed and position, and based on this data, it regulates the stator frequency. In this configuration, there's no risk of the rotor falling out of sync with the stator. The motor essentially governs its own operation, which is why it's referred to as the self-controlled mode.

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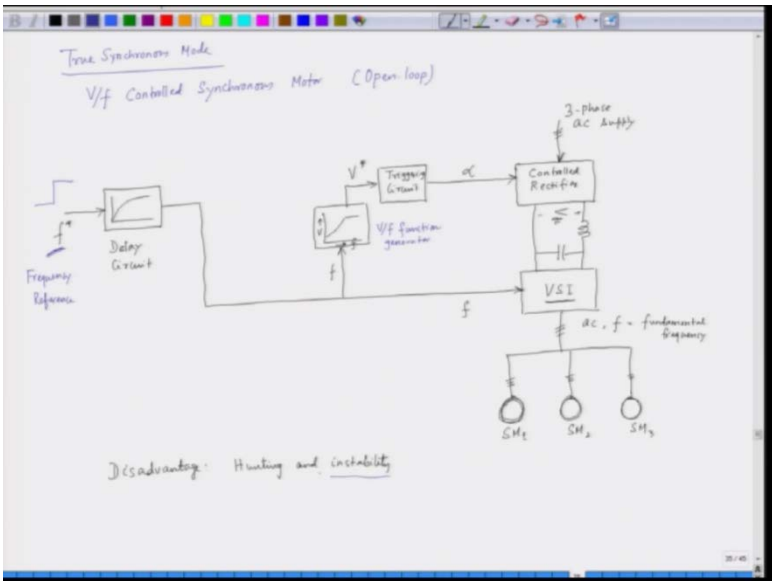

In our previous lecture, we covered the True Synchronous Mode drive, where multiple synchronous motors, let's label them as Motors 1, 2, and 3, are connected in parallel. These motors are powered by a voltage source inverter, which, in turn, is supplied by a controlled rectifier. We have a DC voltage V_{DC} here that serves as the supply voltage, and a filter is incorporated to smooth out any ripples in the DC value before it is fed into the voltage source inverter. As a result, the output is alternating current (AC).

Now, if we want to change the speed of these motors, we adjust the frequency. We establish a frequency command reference, but it’s important to note that this frequency change should not be applied directly to the motors. Instead, it is processed through a delay circuit. Additionally, we need to maintain a constant magnetic flux throughout this process. Similar to an induction motor, we aim to keep the ratio $\frac{V}{f}$ nearly constant up to the base speed. This is managed by a V/f function generator, which outputs a voltage reference.

In fact, we can visualize this relationship with a curve where the y-axis represents voltage and the x-axis represents frequency. By knowing the frequency, we can determine the corresponding voltage. This voltage reference is then sent to the controlled rectifier, which regulates the DC link voltage V_{DC}. Meanwhile, the frequency command is forwarded to the voltage source inverter, enabling it to convert the DC voltage into AC of the same fundamental frequency f.

It's worth mentioning that there is no position feedback in this system. As a result, while this setup is effective, it does have significant drawbacks, particularly regarding stability. The primary disadvantages include issues like hunting and instability. To address these challenges, we can transition to a self-controlled mode for synchronous motor drives. Let's explore this self-controlled mode in more detail.

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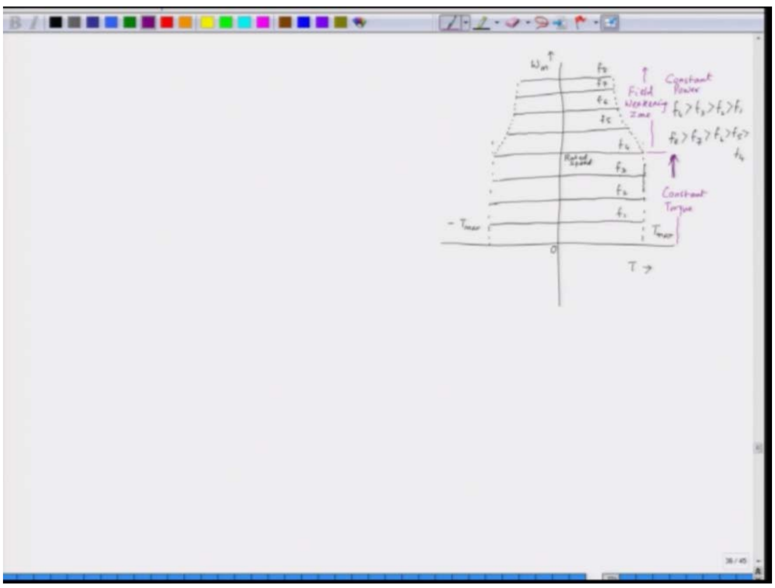

Let’s take a moment to examine the torque-speed characteristics in the True Synchronous Mode. In this scenario, we are varying the frequency, which is depicted on the x-axis as torque and the y-axis as speed. Here, we see that these are constant speed drives, with a maximum torque T_{max} and a corresponding negative maximum torque $-T_{max}$.

Synchronous motor drives, when operated with a nearly constant frequency, essentially function as constant speed drives. This allows us to maintain the same maximum torque, regardless of frequency changes. We can represent various frequency levels, let's say f_1, f_2, f_3, f_4, where $f_4 > f_3 > f_2 > f_1$. As we gradually increase the frequency, the speed remains constant at any given frequency. This means that we can adjust the torque while keeping the speed the same, reinforcing the notion that these are indeed constant speed drives.

Now, let's consider our rated speed. Once we raise this rated speed, we must note that we cannot keep the $\frac{V}{f}$ ratio constant with increasing frequency; instead, we keep the voltage constant. This action results in a reduction of peak torque, which causes the drive to follow a specific trend where the torque diminishes. We can represent additional frequency levels as f_5, f_6, f_7, and f_8, with the relationship $f_8 > f_7 > f_6 > f_5 > f_4$.

This region, where torque decreases with increasing frequency, is referred to as the field weakening zone. From this point onward, moving back to the origin, we encounter the constant torque zone. In this constant torque zone, we maintain a steady torque up to the rated speed. Beyond the rated speed, while we decrease the flux and allow the torque to diminish, the power output remains constant. Thus, this is the speed-torque characteristic of an open-loop, single-motor drive operating under true synchronous mode.

Let's delve into the concept of a self-controlled synchronous motor drive. For our example, we'll consider a self-controlled synchronous motor drive that utilizes a load-commutated thyristor converter, specifically a current source inverter (CSI).

In this system, we have two converters at play. The first is the source-side converter, which employs silicon-controlled rectifiers (SCRs). We also have a DC link that includes a large inductor, designed to maintain a nearly ripple-free current. The second converter is the thyristor converter, composed of six SCRs, which supplies power to the stator of the synchronous motor. Here, we can identify the three phases: phase A, phase B, and phase C.

The synchronous motor operates with a separately excited field, meaning it has its own field winding that is powered by a DC supply. Furthermore, the synchronous motor is equipped with a position sensor, specifically a rotor position sensor, which provides crucial information regarding the rotor's position and frequency.

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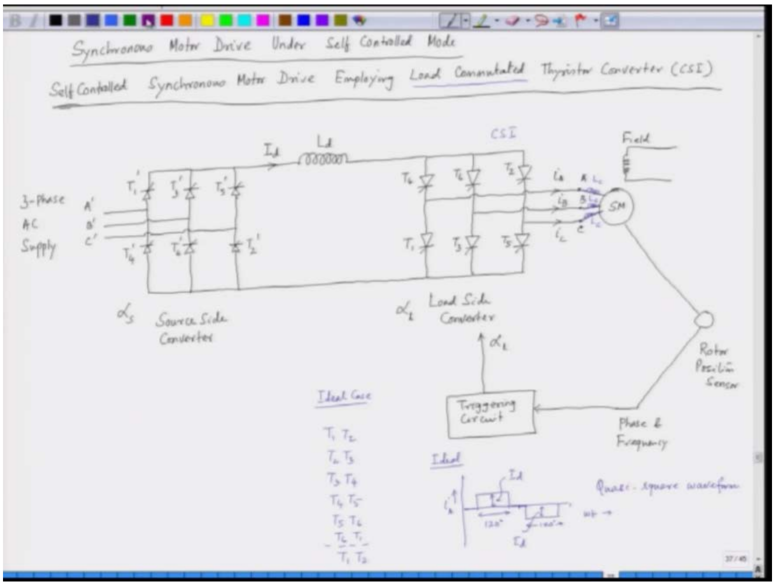

The input to the source-side converter is a three-phase AC supply, which we can label as phase A', phase B', and phase C'. Within the DC link, the large inductor ensures that the DC link current remains nearly constant and free from ripples, allowing for smooth operation.

To control the source-side converter, we trigger it at an angle α_s. This triggering angle is vital for controlling the operation of the source-side converter. On the load side, which connects to the synchronous motor, we have another converter, referred to as the load-side converter. The triggering angle for this converter is denoted as α_l.

Now, how do we trigger the load-side converter? The key lies in the information received from the rotor position sensor, which dictates the timing and angle for triggering this converter. This interplay between the sensors and the converters is essential for the effective operation of the self-controlled synchronous motor drive.

The fundamental principle of a self-controlled synchronous motor drive is that the rotor must be perfectly synchronized with the stator of the synchronous machine. To achieve this synchronization, we rely on information obtained from the rotor position sensor.

In this setup, we have a triggering circuit that receives data from the rotor position sensors. This information includes the rotor angle and phase angle, essentially, we acquire both phase and frequency information. Armed with this data, the triggering circuit generates the appropriate triggering pulses for the load-side converter at a specified angle, denoted as α_l.

The load-side converter can be identified by its six SCRs, which we can label as T_1, T_2, T_3, T_4, T_5, and T_6. Similarly, the source-side converter also consists of six SCRs, which we will label as T_1', T_2', T_3', T_4', T_5', and T_6'. This systematic nomenclature indicates the order in which the SCRs are triggered: after T_6, we return to trigger T_1 once more.

Now, let’s consider the currents flowing into the stator of the synchronous motor, which are represented as i_a, i_b, and i_c. Additionally, the synchronous motor generates an induced electromotive force (EMF) or back EMF, and each phase will also have its own inductance. We can denote these inductances as L_A, L_B, and L_C for phases A, B, and C, respectively. These inductances are referred to as commutating inductances.

The load-side converter, which comprises SCRs, is also referred to as a Current Source Inverter (CSI). This converter operates through load commutation, where it is commutated by the back EMF of the synchronous machine. Unlike other types of converters, SCRs do not possess a commutation circuit; rather, they rely on the back EMF to turn them off once they have been triggered. This characteristic is what defines it as a load-commutated thyristor converter.

Now, let's delve into the commutation process. The triggering pattern for the SCRs follows a sequence like this: T_1, T_2, T_3, T_4, T_5, T_6, T_1, T_2, and it continues in this manner. In any given moment, two SCRs in the load-side converter are turned on simultaneously; for example, T_1 and T_2. This represents the ideal scenario.

When we examine the load current i_a, the ideal waveform for the current produced by a CSI resembles a quasi-rectangular shape. To illustrate, the amplitude of the load current is represented as I_d, which is equal in the negative direction as well. This waveform is plotted against θ or ω t, with the angles corresponding to 0, π (or 180 degrees), and 2π (or 360 degrees). Each pulse duration spans 120 degrees, both for the positive and negative portions of the waveform, resulting in a quasi-square waveform.

However, it is important to note that due to the inductance present in the phases, the current changes will not be as abrupt as the ideal waveform suggests. In reality, the practical current change will exhibit a smoother transition, deviating from the sharp edges of the ideal waveform. Thus, while the ideal representation offers a good baseline, actual operational conditions reveal a more gradual current change profile.

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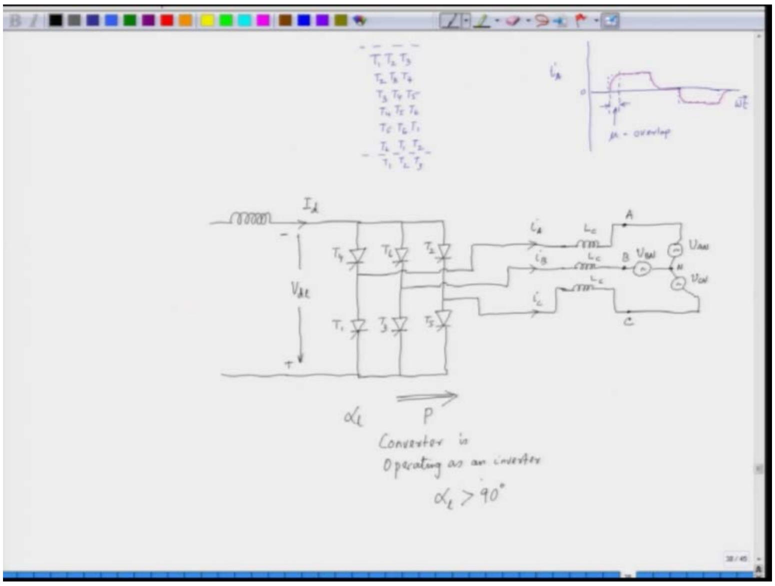

When we examine the practical changes in current, we notice that they differ significantly from what we previously discussed regarding the ideal waveform. The ideal waveform represents a certain behavior, but the practical scenario presents a more complex picture. On the ω t axis, which is our x-axis, the practical waveform appears delayed. This waveform represents the phase current i_a, and this delay is referred to as the overlap angle, denoted by μ.

This overlap angle arises because, during the conduction process, there is a moment when one SCR remains active while the next one is triggered. For instance, when we trigger T_3, T_1 does not turn off immediately; instead, it takes some time for the transition. This gradual conduction is essential to understanding how the system operates.

Now, let's illustrate the commutation process by sketching the circuit diagram. We have the load-side converter, and for our analysis, we can represent the load with the back EMF sources. In this setup, we also depict the inductances associated with the machine's various phases. These phases include V_{AN}, V_{BN}, and V_{CN}, which connect to a neutral point.

The machine's inductances, denoted as L_C, play a crucial role in this system. For clarity, we have the phase A current i_a, the phase B current, and the phase C current i_c. Additionally, we include the DC link, which contains an inductance, with the current through the DC link represented as i_d.

Now, let's consider the SCRs in our system, labeled as T_1, T_2, T_3, T_4, T_5, and T_6. To analyze the commutation process, we will draw the voltage waveforms for the different phases. We will illustrate the voltage waveforms for phase A, phase B, and phase C.

Since the load is an active load, it generates a back EMF, which results in sinusoidal load voltages. Therefore, we can sketch the various line voltages for the synchronous machine, specifically V_{AB}, V_{BC}, and V_{CA}. This depiction provides a comprehensive view of how the synchronous motor drive functions under self-controlled conditions.

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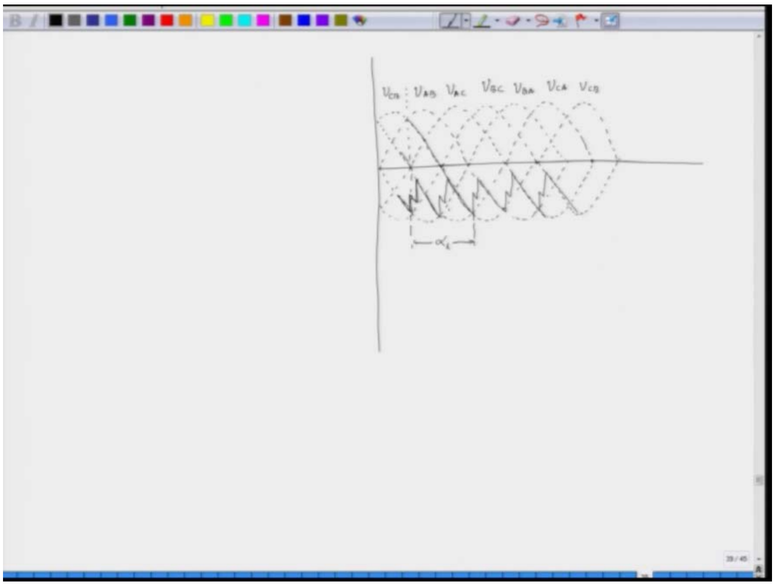

Let's illustrate the load voltages in our system. We begin with one of the load voltages, denoted as V_{AB}. Following this, we have the second load voltage, V_{BC}, which is phase-shifted by 120 degrees from V_{AB}. Finally, we introduce the third load voltage, V_{CA}. Additionally, we can represent the inverses of these voltages: V_{AC}, V_{BA}, and V_{CB}.

All these waveforms exhibit symmetry, which means that if we were to observe them on an oscilloscope, we would clearly see the various three-phase voltage waveforms. For instance, V_{CB} would appear as one of the actual waveforms displayed.

At this point, our objective is to analyze the commutation process. We will start from a specific instant, where our expected voltage should ideally be V_{AB}. However, we introduce a delay, applying a triggering angle denoted as α_L. This triggering angle α_L allows us to switch to V_{AB}, and during this transition, we encounter a commutation overlap.

Similarly, at the next instant, we trigger the adjacent SCR, leading to another commutation overlap. This pattern continues as we apply triggering pulses, with each instance resulting in an overlap that alters the output waveform accordingly. This sequence creates a characteristic output, which we can observe.

When we analyze the overall output of the converter, particularly the DC voltage, we see that the DC voltage $V_{D_{\text{load side}}}$ takes on a certain shape, represented as + and - fluctuations. It's essential to note that this inverter or converter operates in the inverting mode, meaning energy is supplied from the DC source to the motor. This signifies a flow of power P from the converter to the motor.

Given that the converter operates as an inverter, we find that the triggering angle α_L exceeds 90 degrees. This condition implies a gradual transition from one SCR to another. We will discuss the analysis of the commutation process in our next lecture, where we will explore these dynamics in greater detail.